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Short-Range Ultra-Wideband Systems

ABSTRACT

This report describes UWB MURI activities from 1 May 2001 to 31 October 2006. The problems singled out in this research have two characteristics: They are caused by the extreme fractional bandwidth of ultra-wideband (UWB) radio, and they cannot be solved directly by conventional means. The major contributions of this UWB research effort are in the areas of link budget analysis, signal design, antenna/spice simulation, UWB receiver architecture and design in CMOS, low-complexity transmitted reference systems, rapid signal acquisition, channel capacity and security, etc. The 27 journal papers and 83 conference papers published under this program included four award-winning papers.

Thirteen hardware components and systems were fabricated, including an UWB transceiver on a chip, an frequency-shifted UWB transmitted reference system, and a UWB radar for short-range imaging in free space and in a through-the-wall mode. This contract also co-sponsored work on two simulation efforts – the Berkeley Emulation Engine and the UMass UWB Link Simulator.

Technology transfer was supported by six MURI sponsored meetings, including two UWB Workshops, and 29 talks at meetings supported by other entities.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

[J1] W. Namgoong, “A Channelized Digital Ultra-Wideband Receiver,” IEEE Transactions on Wireless Communications, May 2003, pp. 502-510.

[J2] David M. Pozar, “Closed-Form Approximations for Link Loss in an UWB Radio System Using Small Antennas,” IEEE Trans. Antennas and Propagation, September 2003.

[J3] David M. Pozar, “Waveform Optimizations for Ultra-Wideband Radio Systems,” IEEE Transactions on Antennas and Propagation, September 2003.

[J4] K. Kuusilinna, C. Chang, M.J. Ammer, B. Richards, R.W. Brodersen, “Designing BEE: a Hardware Emulation Engine for Signal Processing in Low-Power Wireless Applications,” EURASIP Journal on Applied Signal Processing (Special Issue on Rapid Prototyping of DSP Systems), May 2003.

[J5] Eric Homier and R. A. Scholtz, “A Generalized Signal Flow Graph Approach for Hybrid Acquisition of Ultra-Wideband Signals”, International Journal of Wireless Information Networks (Special Issue on Ultrawideband Radio), October 2003.

[J6] J. Lerdworatawee, W. Namgoong, “Low Noise Amplifier Design for Ultra-Wideband Radio”, IEEE Trans. on Circuits and Systems I - Regular Papers, vol. 51, June 2004, pp. 1075-1087.

[J7] W. Namgoong, J. Lerdworatawee, “Noise Figure of Digital Communication Receivers Revisited,” IEEE Trans. on Circuits and Systems I - Regular Papers, vol. 51, July 2004, pp. 1330-1335.

[J8] R. A. Scholtz, David Pozar, and Won Namgoong, “Ultrawideband Radio: A Tutorial,” EURASIP Journal on Applied Signal Processing (Special Issue on Ultrawideband Radio), pp. 252-272, vol. 3, 2005.

[J9] Keith M. Chugg and Mingrui Zhu, “A New Approach to rapid PN Code Acquisition Using Iterative Message Passing Techniques,” IEEE Journal of Selected Areas in Communications (Special Issue on Military Communications), vol. 23, no. 5, May 2005, pp. 884-897.

[J10] Mike S.W. Chen, Robert W. Brodersen, “A Subsampling UWB Impulse Radio Architecture Utilizing Analytic Signaling,” IEICE Trans. on Electronics, vol. E88-C, No. 6, June 2005 (invited paper).

[J11] I. D. O'Donnell, R. W. Brodersen, “An Ultra-Wideband Transceiver Architecture for Low Power, Low Rate, Wireless Systems,” IEEE Trans. on Vehicular Technology (Special Section on Ultra-wideband (UWB) Wireless Communications – A New Horizon), v. 54(5), September 2005, pp. pp. 1623-1631.

[J12] Y. Chao and R. Scholtz, “Ultra-Wideband Transmitted Reference Systems,” IEEE Trans. on Vehicular Technology (Special Section on Ultra-wideband (UWB) Wireless Communications – A New Horizon), v. 54(5), September 2005, pp. 1556-1569.

[J13] L. Feng and W. Namgoong, “An Oversampled Channelized UWB Receiver with Transmitted Reference Modulation,” IEEE Trans. on Wireless Communications, to be published.

[J14] L. Feng and W. Namgoong, “An Adaptive Maximally Decimated Channelized UWB Receiver with Cyclic Prefix,” IEEE Trans. on Circuits and Systems I - Regular Papers, vol. 52, Oct. 2005, pp. 2165-2172.

[J15] J. Lerdworatawee, W. Namgoong, “Wideband Low Noise Amplifier Design Based on Source Degeneration Topology,” IEEE Trans. on Circuits and Systems I - Regular Papers, vol. 52, Nov. 2005, 2327-2334.

[J16] O. W. Yeung and K. M. Chugg, “An Iterative Algorithm and Low Complexity Hardware Architecture for Fast Acquisition of PN Codes in UWB Systems”, J. VLSI Signal Processing (special issue on Ultrawideband Systems), April 2006.

[J17] A. O. Boryssenko and D. H.Schaubert, “Electromagnetics-Related Aspects of Signaling and Signal Processing for UWB Short Range Radios,” J. VLSI Signal Processing (special issue on Ultrawideband Systems), April 2006, v. 43(1) pp. 89-104.

[J18] H. Zhang, D. L. Goeckel, S. Wei, and M. Z. Win, “Rapid Hybrid Acquisition of Ultra-Wideband Signals,” J. VLSI Signal Processing (special issue on Ultrawideband Systems), April 2006, v. 43(1) pp. 7-23.

[J19] L. Feng and W. Namgoong, “An Analog/Digital Baseband Processor Design of a UWB Channelized Receiver for Transmitted Reference Signals,” J. VLSI Signal Processing (special issue on Ultrawideband Systems), April 2006, v. 43(1) pp. 59-71.

[J20] I. D. O’Donnell and R. W. Brodersen, “A 2.3 mW Baseband Impulse-UWB Transceiver Front-end in CMOS,” IEEE VLSI Circuits Digest of Technical Papers (VLSI ’06) June 2006.

[J21] S. Wang, A. Niknejad and R. Brodersen, “Circuit Modeling Methodology for UWB Omnidirectional Small Antennas,” IEEE Journal of Selected Areas in Communications: Special Issue on Ultra-wideband Communications (Special Issue on Ultra-Wideband Wireless Communications – Theory and Applications), v.24(4), April 2006, pp. 871-877.

[J22] J. Lerdworatawee, W. Namgoong, “Revisiting Spurious Free Dynamic Range of Communication Receivers,” IEEE Trans. on Circuits and Systems I - Regular Papers, vol. 53, April 2006, pp. 937-943.

[J23] A.O. Boryssenko and D.H. Schaubert, “Antenna Link Transfer Function Factorization Applied to Optimized Channel Design”, IEEE Trans. Antennas and Propagation, vol. 54, no. 10, pp. 2878-2889, October 2006.

[J24] D. Porrat, D. N. C. Tse and S. Nacu, “Channel Uncertainty in Ultra Wideband Communication Systems,” IEEE Transactions on Information Theory, accepted pending revisions.

[J25] T. R. Halford, A. J. Grant, and K. M. Chugg, “Which Codes Have 4-Cycle-Free Tanner Graphs?” accepted for publication in IEEE Transactions on Information Theory.

[J26] J. Lerdworatawee, W. Namgoong, "Generalized Linear Periodic Time-Varying Analysis for Noise Reduction in an Active Mixer," accepted for publication in IEEE Journal of Solid-State Circuits.

[J27] R. Wilson, D. Tse, and R. A. Scholtz, “Channel Identification: Secret Sharing Using Reciprocity in Ultrawideband Channels,” accepted (pending revisions) by IEEE Transactions on Information Forensics and Security.

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(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

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Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

[T1] R. A. Scholtz, “UWB Radio,” Time Domain Corporation Seminar, Huntsville, AL, June 7, 2001.
[T2] R. A. Scholtz, “Remarks on UWB Radio Research,” Information Sciences Institute Seminar, Marina del Rey, CA, September 6, 2001.
[T3] R. A. Scholtz, “Remarks on UWB Radio,” DARPA’s NETEX Program Industry Day, McLean, VA, September 10, 2001.
[T4] R. A. Scholtz, “UWB Radio,” Third IEEE Workshop on WLAN, Newton, MA, September 27-28, 2001.
[T5] R. A. Scholtz, “Ultra-Wideband Radio Research,” Intel Ultrawideband Forum, October 11-12, 2001.
[T6] R. Brodersen, “Ultra-wideband Baseband System Architecture and Simulations,” Berkeley Wireless Research Center Winter retreat, January 8, 2002.
[T7] R. Brodersen, “Ultra-wideband Antenna Simulations,” Berkeley Wireless Research Center Winter retreat, January 8, 2002.
[T8] R. A. Scholtz, “Ultrawideband Radio,” Magis Networks, San Diego CA, February2002.
[T9] R. A. Scholtz, Ultra-Wideband Radio Panel, WCNC 2002, Orlando FL, March 2002.
[T10] D. L. Goeckel, Emerging Theory and Applications Panel, NSF/ONR/ARO/ARL-CTA “Future Challenges on Signal Processing and Communications in Wireless Networks” Workshop, Cornell University, September 2002.
[T11] D.H. Schaubert, “Short-Range Ultra-Wideband Systems,” presentation to Mead-Westvaco, September 2002.
[T12] D.H. Schaubert, “Overview of UWB antenna research for communication”, presentation at ASTRON, Dwingeloo, The Netherlands, October 2002.
[T13] R. A. Scholtz, “Ultrawideband: Past, Present, and Future,” Berkeley Wireless Research Center, Winter Retreat, January 13-14, 2003.
[T14] R. A. Scholtz, “Ultrawideband Radio,” Communication Theory Workshop. Mesa, AZ April 9, 2003.
[T15] R. W. Brodersen, “19 GHz of Unlicensed Bandwidth”, IEEE Communications Society ECV, September 2003.
[T16] R. A. Scholtz (plenary speaker), “Ultrawideband Promises and Problems,” 2003 IEEE Topical Conference on Wireless Communication Technology, October 15-17, 2003.
[T17] R. A. Scholtz (International Expert, one of three), Thematic Workshop on UWB Technologies and Pervasive Computing, Singapore, October 6-7, 2003.
[T18] D.L. Goeckel, “Generalized Transmitted-Reference UWB Systems,” presentation at the University of Virginia, November 2003.
[T19] R. A. Scholtz, “Ultrawideband Radio,” USC Communication Sciences Institute Review, February 26, 2004.
[T20] R. A. Scholtz, “Looking for the Ultrawideband Communications Niche,” Raytheon Corporation, Fullerton CA, April 27, 2004.
[T21] R. A. Scholtz, “Looking for the Ultrawideband Communications Niche,” plenary address, joint meeting of the International Workshop on Ultra Wideband Systems and the Conference on Ultra Wideband Systems and Technologies, Kyoto, Japan, May 19, 2004.
[T22] R. A. Scholtz, workshop presentation: ``Getting the Most out of UWB Propagation Measurements," RAWCON, Atlanta GA, September 19. 2004.
[T23] W. Namgoong, “UWB Digital Receiver Design Techniques,” Massachusetts Institute of Technology, May 18, 2005.
[T24] W. Namgoong, “UWB Digital Receiver Design Techniques,” UCLA, May 20, 2005.
[T25] R. A. Scholtz, “Ultrawideband Radio – Realities and Promises,” 2005 Texas Wireless Symposium, Austin Texas,October 27, 2005.
[T26] R. A. Scholtz, panelist, Wireless Visionaries, 100Mbps anytime, anywhere? 2005 Texas Wireless Symposium, Austin Texas,October 26, 2005.
[T27] R. A. Scholtz, “Ultrawideband Radio – Has It Arrived?” UCSD Symposium on Spectrally Efficient Wireless, November 17, 2005.
[T28] D. L. Goeckel, “Slightly Frequency-Shifted Ultra-Wideband Radio,” Mitsubishi Electronics Research Laboratory (MERL), September 2006.
[T29] R. A. Scholtz, “Recent Results and Challenges in Ultrawide Bandwidth Radio Systems,” plenary address, ICUWB 29006, Waltham MA, Septembr 26, 2006.

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[C1] W. Namgoong, “A Channelized DSSS Ultra-Wideband Receiver,” 2001 IEEE Proc. Radio and Wireless Conference.

[C2] R. D. Wilson, R. D. Weaver, M.-H. Chung and R. A. Scholtz, “Ultra-Wideband Interference Effects on an Amateur Radio Receiver,” IEEE Conference on Ultra Wideband Systems and Technologies, 2002.

[C3] E. A. Homier and R. A. Scholtz, “Rapid Acquisition of Ultra-Wideband Signals in the Dense Multipath Channel,” IEEE Conference on Ultra Wideband Systems and Technologies, 2002.

[C4] A. Taha and K. M. Chugg, “On Designing the Optimal Template Waveform for UWB Impulse Radio in the Presence of Multipath,” IEEE Conference on Ultra Wideband Systems and Technologies, 2002.

[C5] A. Taha and K. M. Chugg, “Multipath Diversity Reception of Wireless Multiple Access Time-Hopping Digital Impulse Radio,” IEEE Conference on Ultra Wideband Systems and Technologies, 2002.

[C6] Anatoliy O. Boryssenko and Daniel H. Schaubert, “Optimized Ultra-Wideband Radiation of Dipole Antennas with Triangle Driving Pulses,” The AMEREM 2002 Symposium, Annapolis, MD, June 2-7, 2002.

[C7] Anatoliy O. Boryssenko and Daniel H. Schaubert, “Time-Domain Integral-Equation-Based Solver for Transient and Broadband Problems in Electromagnetics,” The AMEREM 2002 Symposium, Annapolis, MD, June 2-7, 2002.

[C8] J. Lerdworatawee, W. Namgoong, “MSSE Matching for Low Noise Amplifier,” IEEE Symposium on Circuits and Systems, 2002.

[C9] K. Kuusilinna, C. Chang, R. Brodersen, G. Wright, “BEE: A Large-scale FPGA-based Emulation Engine,” FPGA2002, Monterey CA, 2002. (This poster presentation is superceded by [C15].)

[C10] I. D. O’Donnell, M. S. W. Chen, S. B .T. Wang, R. W. Brodersen, “An Integrated, Low Power, Ultra-Wideband Transceiver Architecture for Low-Rate, Indoor Wireless Systems,” IEEE CAS Workshop on Wireless Communications and Networking, Sept. 5-6, 2002.

[C11] D. Thirupathi and K. M. Chugg, “A Simple Low Rate Turbo-Like Code Design for Spread Spectrum Signals,” Proceedings of the 2002 Asilomar Conference on Signals, Systems, and Computers, Monterey, CA, November 2002.

[C12] Ali Taha and Keith M. Chugg, “A Theoretical Study on the Effects of Interference on UWB Multiple Access Impulse Radio,” Asilomar Conference on Signals, Systems and Computers, Monterey CA, November, 2002.

[C13] H. Zhang, S. Wei, D. Goeckel, and M. Win, “Rapid Acquisition of Ultra-Wideband Radio Signals” (invited), Proceedings of the 2002 Asilomar Conference on Signals, Systems, and Computers, Monterey, CA, November 2002.

[C14] D. Thirupathi and K. M. Chugg, “ A Simple Construction of Low Rate Convolutional Codes with Application to Low Rate Turbo-like Code Design,” 2002 IEEE Globecom Conf., Taipei, Taiwan, December 2002.

[C15] C. Chang, K. Kuusilinna, B. Richards, R.W. Brodersen, “Implementation of BEE: a Real-time Large-Scale Hardware Emulation Engine,” 11th ACM International Symposium on Field-Programmable Gate Arrays, FPGA 2003, Monterey, CA, February 2003.

[C16] W. Namgoong, J. Lerdworatawee, “Revisiting the Noise Figure Design Metric for Digital Communication Receivers” (invited paper), International Symposium of Quality Electronic Design, San Jose, CA, March 2003.

[C17] J. Lerdworatawee, W. Namgoong, “Low Noise Amplifier Design for Ultra-Wideband Radio,” IEEE Symposium on Circuits and Systems, Bangkok, Thailand, May 2003.

[C18] D. Thirupathi and K. M. Chugg, “Construction of Coset-based Low Rate Convolutional Codes and Their Application to Low Rate Turbo-Like Code Design,” IEEE International Communications Conference, Anchorage AK, June 2003.

[C19] W. Namgoong, “Channelized Digital Receivers for Impulse Radio,” IEEE International Communication Conference, Anchorage AK, June 2003.

[C20] E. Homier and R. Scholtz, “Hybrid Fixed-Dwell Time Search Techniques for Rapid Acquisition of Ultra-Wideband Signals,” International Workshop on Ultra-Wideband Systems, Oulu, Finland, June 2003.

[C21] A. Klein, D. R. Brown, D. Goeckel, and C. R. Johnson, "Rake Reception for UWB Communication Systems with Intersymbol Interference," 2003 Signal Processing Advances for Wireless Communications (SPAWC) Conference, June 2003.

[C22] A. Medi, and W. Namgoong, "A Fully Integrated Multi-Output CMOS Frequency Synthesizer For Channelized Receivers", IEEE International SOC Conference, Portland, Oregon, September 2003.

[C23] A. Taha and K. Chugg, "On the Power Spectral Density of Wireless Multiple-Access UWB Impulse Radio Under Realistic Propagation Conditions," Vehicular Technology Conference, October 2003.

[C24] D. Porrat and D. N. C. Tse, "Bandwidth Scaling in Ultra Wideband Communications," Allerton Conference on Communication, Control, and Computing, October 2003.

[C25] M. Zhu and K. M. Chugg, "Iterative Message-Passing Algorithms for Rapid PN Code Acquisition" (invited paper), IEEE Conference on Military Communications (MILCOM), Boston, MA, November 2003.

[C26] L. Feng, W. Namgoong, "Joint Estimation and Detection of UWB Signals with Timing Offset Error and Unknown Channel", IEEE Ultra Wideband Systems and Technologies, Reston VA, November 2003.

[C27] H. Zhang and D. Goeckel, "Generalized Transmitted Reference UWB Systems," IEEE Ultra Wideband Systems and Technologies, Reston VA, November 2003.

[C28] W. Namgoong, J. Lerdworatawee, "Amplification of Ultrawideband Signals," IEEE International Conference on Computer Aided Design, San Jose CA, November 2003.

[C29] Chee-Cheon Chui and R. A. Scholtz, "Tracking UWB monocycles in IEEE 802.15 Multi-path Channels," Asilomar Conference on Signals, Systems, and Computers, November 2003.

[C30] Meng-Hsuan Chung and R. A. Scholtz "Optimization of Delay Tracking Loops for Binary Modulated Systems," Asilomar Conference on Signals, Systems, and Computers, November 2003.

[C31] Robert Wilson and R. A. Scholtz, "Template Estimation in UWB Radio," Asilomar Conference on Signals, Systems, and Computers, November 2003.

[C32] R. D. Wilson and R.A Scholtz, "Comparison of CDMA and Modulation Schemes for UWB Radio in a Multipath Environment," Globecom, December 2003.

[C33] C. C. Chui and R. A. Scholtz, "Optimizing Tracking Loops for UWB Monocycles," Globecom, December 2003.

[C34] Y.-L. Chao and R. A. Scholtz, "Optimal and Suboptimal Receivers for Ultra-Wideband Transmitted Reference Systems," Globecom, December 2003.

[C35] Y. Chao and R. Scholtz, "Multiple Access Performance of Ultra-Wideband Transmitted Reference Systems," IEEE Wireless Communications and Networking Conference (WCNC 04), vol. 3, March 2004.

[C36] L. Feng, W. Namgoong, "An Oversampled Channelized Ultra-Wideband Receiver," IEEE Conference on Ultra Wideband Systems and Technologies, Kyoto, Japan, May 2004.

[C37] M. Chen, R. Brodersen, "A Subsampling UWB Radio Architecture by Analytic Signaling," International Conference on Acoustics, Speech, and Signal Processing (ICASSP), May 2004.

[C38] A.O. Boryssenko and D.H. Schaubert, "Efficient and Practical Pulses for Dipole Antenna UWB Link", Proceeding of IEEE Antenna & Propagation Symposium, vol. 2, June 2004, pp. 1283-1286.

[C39] R. Wilson and R. A. Scholtz, "On the Dependence of UWB Impulse Radio Link Performance on Channel Statistics," IEEE International Conference on Communications, vol. 6, June 2004.

[C40] S. B. Wang, A. M. Niknejad, and R. W. Brodersen, "Modeling Omnidirectional Small Antenna for UWB Applications," IEEE International Symposium on Antennas and Propagation, June 2004.

[C41] A.O. Boryssenko, D.H. Schaubert, “Optimized Antenna and Signal Co-Design for UWB Antenna Link”, To be published in: Ultra-Wideband Short-Pulse Electromagnetics 7, 2006.

[C42] L. Feng, W. Namgoong, “Oversampled Channelized Receiver for Transmitted Reference UWB System in the Presence of Narrowband Interference,” IEEE Workshop on Signal Processing Systems, Austin TX, October 2004.

[C43] M. S.W. Chen, R. W. Brodersen, “The Impact of a Wideband Channel on UWB System Design”, IEEE Military Communications Conference, Monterey CA, November 2004.

[C44] M. Nemati and R. Scholtz, “A Diffusion Model for UWB Indoor Propagation,” IEEE Military Communications Conference, Monterey CA, November 2004.

[C45] C. Chui and R. A. Scholtz, “A Synchronizing Scheme for an Impulse Network,” accepted by IEEE Military Communications Conference, Monterey CA, November 2004.

[C46] M. Chung and R. A. Scholtz, “A Comparison of Transmitted- and Stored Reference Systems for Ultra-Wideband Communications,” IEEE Military Communications Conference, Monterey CA, November 2004.

[C47] S. Chang and R. Scholtz, “Polarization Measurements in a UWB Multipath Channel,” IEEE Military Communications Conference, Monterey CA, November 2004.

[C48] Durai Thirupathi and Keith M. Chugg , “Symbol Synchronization in Coded UWB Systems using Adaptive Iterative Detection,” IEEE Military Communications Conference, Monterey CA, November 2004.

[C49] C. Chui and R. A. Scholtz, “Estimating Parameters of Received UWB Monocycles,” Asilomar Conference on Signals, Systems, and Computers, November 2004.

[C50] Y. Chao and R. Scholtz, “Novel Ultra-wideband Transmitted Reference Systems,” Asilomar Conference on Signals, Systems, and Computers, November 2004.

[C51] T. Lewis and R. Scholtz, “Optimal UWB Waveform Synthesis with Power Spectral Density Constraints,” Asilomar Conference on Signals, Systems, and Computers, November 2004.

[C52] Y. Chao, “Optimal Integration Time for Ultra-Wideband Transmitted Reference Correlation Receivers,” Asilomar Conference on Signals, Systems, and Computers, November 2004.

[C53] Y. Chao and R. Scholtz, “Weighted Correlation Receivers for Ultra-Wideband Transmitted Reference Systems,” IEEE Global Telecommunications Conference, v1, pp. 66-70, December 2004.

[C54] K. Lee and W. Namgoong, “A0.25um CMOS 3-bit 12.5Gsamples/s Frequency Channelized Receiver for Serial Links,” IEEE International Solid-State Circuits Conference (ISSCC), San Francisco CA, February 2005.

[C55] M. Chung and R. Scholtz, “Receiver improvement for ultra-wideband transmitted-reference systems,” Wireless Communications and Networking Conference (WCNC), v.2, pp. 746-751, March 2005.

[C56] Z. Ebrahimian and R. Scholtz, “Source Localization Using Reflection Omission in the Near-Field,” IEEE-ACES Conference on Wireless Communications and Applied Computational Electromagnetics, Honolulu HI, April 3-7, 2005.

[C57] Z. Ebrahimian and R. Scholtz, "Receiver Sites for Accurate Indoor Position Location Systems", IEEE-ACES Conference on Wireless Communications and Applied Computational Electromagnetics, Honolulu HI, April 3-7, 2005.

[C58] W. Namgoong, L. Feng, “Digitizing of UWB Signals Based on Frequency Channelization” (Invited), IEEE International Symposium on Circuits and Systems (ISCAS), May 2005, Kobe, Japan.

[C59] L. Feng, W. Namgoong, “An Adaptive Maximally Decimated Channelized UWB Receiver with Cyclic Prefix”, IEEE International Conference on Communications (ICC), May 2005, Seoul, Korea.

[C60] D.L. Sostanovsky, A.O. Boryssenko, E.S. Boryssenko, "UWB Radar Imaging System with Two-Element Receiving Array Antenna," 5th International Conference on Antenna Theory and Technique, Kiev, Ukraine, May 2005, pp. 357-360.

[C61] S. Wang, A. Niknejad and R. Brodersen, "A sub-mW 960-MHz Ultra-Wideband CMOS LNA," IEEE Radio-Frequency Integrated Circuits(RFIC) Symposium, pp. 35-38, June 2005.

[C62] J. Lerdworatawee, W. Namgoong, "Generalized Noise Analysis of Active Mixers by Simple Linear Periodic Time-Varying Circuit Model," IEEE Custom Integrated Circuits Conference (CICC), San Jose CA, September 2005.

[C63] A.O. Boryssenko and D.L. Sostanovsky, "A New Two-Flare-Shaped UWB Antenna Element," Proceedings of 2005 Antenna Applications Symposium, September 2005, pp. 451-471.

[C64] L. Feng, W. Namgoong, "Digitizing Ultra-Wideband OFDM Signals with Frequency Channelization", IEEE Military Communications Conference (MILCOM), Atlantic City NJ, October 2005.

[C65] D. Goeckel and Q. Zhang, "Slightly Frequency-Shifted Reference Ultra-Wideband (UWB) Radio: TR-UWB without the Delay Element," 2005 Military Communications Conference, October 2005.

[C66] M. Zhu and K. M. Chugg, "Lower Bounds on Stopping Distance of Linear Codes and Their Applications," Proceedings of the Allerton Conference Communication, Control, and Computing, October 2005.

[C67] O. Yeung and K. M. Chugg, "An Iterative Algorithm and Low Complexity Hardware Architecture for Fast Acquisition of Long PN Codes," Proceedings of the Allerton Conference Communication, Control, and Computing, October 2005.

[C68] L. Feng, W. Namgoong, "Generalization of Single-Carrier and Multicarrier Cyclic Prefixed Communication", IEEE Global Telecommunication Conference (Globecom), Nov. 2005, St. Louis, Missouri.

[C69] L. Feng, W. Namgoong, "Fast Acquisition for Transmitted Reference Ultra-Wideband Systems with Channelized Receiver," 39th Asilomar Conference on Signals, Systems, and Computers, Pacific Grove CA, November 2005.

[C70] M. Nemati and R. Scholtz, "A Parametric Analytical Diffusion Model for Indoor Ultra-Wideband Received Signal," 39th Asilomar Conference on Signals, Systems, and Computers, Pacific Grove CA, November 2005.

[C71] Y. Chen and R. A. Scholtz, "A theoretical Model of a Voltage-Controlled Oscillator," 39th Asilomar Conference on Signals, Systems, and Computers, Pacific Grove CA, November 2005.

[C72] A. Medi and W. Namgoong, "A Fully Integrated Low Cost Packaged CMOS Low Noise Amplifier for UWB Radio," IEEE Radio and Wireless Symposium (RWS), San Diego CA, January 2006.

[C73] Q. Zhang and D. L. Goeckel, "Multi-Differential Slightly Frequency-Shifted Reference Ultra-wideband (UWB) Radio," Conference on Information Sciences and Systems (CISS), March 2006.

[C74] T. R. Halford, A. J. Grant, and K. M. Chugg, "Which Codes Have 4-Cycle-Free Tanner Graphs?" IEEE International Symposium on Information Theory, Seattle WA, July 2006.

[C76] S. Chang and R. Scholtz, "UWB Wave Polarization Measurements in Indoor Channels with a Hertzian Dipole Antenna Approximation," Antennas and Propagation Society International Symposium 2005, Albuquerque, NM, July 2006.

[C77] A. O. Boryssenko and D. H. Schaubert, "Dispersive Properties of Terminal-Loaded Antennas in UWB Link," 2006 Antenna Applications Symposium, September 2006.

[C78] I. D. O'Donnell and R. W. Brodersen, "A Flexible, Low-Power, Baseband Impulse-UWB Transceiver Front-end," ICUWB'06, September 2006.

[C79] A. O. Boryssenko, D. H. Schaubert, "Optimal Port Loading Conditions for Dipole Antennas Operating in UWB Links", Int. Conference on UWB, Boston, September 2006, pp. 333-338.

[C80] A. O. Boryssenko, D. H. Schaubert, "Antenna-Circuit-Signal Co-Design for UWB Systems", (invited), Int. Conf. on Ultrawideband

and Ultrashort Impulse Signals, September 2006, Sevastopol, Ukraine, pp. 97-102.

[C81] Majid A. Nemati, Urbashi Mitra, Robert A. Scholtz,"Optimum integration time for UWB transmitted reference and energy detector receivers", MILCOM2006, Washington, D.C., 23-25 Oct. 2006.

[C82] A. O. Boryssenko, D. H. Schaubert, “Dispersion Properties of Terminal-Loaded Dipole Antennas in UWB Link”, To be published in Ultra-Wideband Short-Pulse Electromagnetics 8.

[C83] A. O. Boryssenko, et al, “Portable Imaging UWB Radar System with Two-Element Receiving Array”, To be published in Ultra-Wideband Short-Pulse Electromagnetics 8.

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 83

(d) Manuscripts

[S1] Durai Thirupathi and Keith M. Chugg, “On the construction of low rate trellis codes with application to low rate turbo-likecode design,” submitted to IEEE Trans. on Communications.

[S2] D. Goeckel and Q. Zhang, "Slightly Frequency-Shifted Ultra-Wideband (UWB) Radio," submitted to IEEE Transactions on Communications.

[S3] D. Thirupathi and K. M. Chugg, “Frame Synchronization and Channel Acquisition in Coded Impulse Radio Systems,” submitted to IEEE J. Selected Areas in Communications.

[S4] J. Lerdworatawee, W. Namgoong, "Revisiting Spurious Free Dynamic Range for Wideband Communication Systems," submitted to IEEE Trans. on Circuits and Systems I - Regular Papers.

[S5] L. Feng, W. Namgoong, "Generalization of Single-Carrier and Multicarrier Cyclic Prefixed Communication," submitted to IEEE Trans. on Communications.

[S6] J. Lerdworatawee, W. Namgoong, "Noise Analysis in CMOS Active Mixer and Flicker Noise Reduction," submitted to IEEE Journal of Solid-State Circuits.

[S7] Mingrui Zhu and Keith M. Chugg, “Bounds on the Expansion Properties of Tanner Graphs,” submitted to IEEE Trans. Information Theory.

[S8] D. M. Pozar, “Optimal Radiated Waveforms from an Arbitrary UWB Antenna,” submitted to IEEE Transactions on Antennas and Propagation.

[S9] L. Feng, W. Namgoong, "Generalization Cyclic Prefixed Communication with Interleaved Discrete Fourier Transforms," submitted to IEEE Trans. on Communications.

[S10] T. R. Halford and K. M. Chugg, “Random Redundant Iterative Soft-In Soft-Out Decoding,” submitted to the IEEE Transactions on Information Theory.

[S11] Q. Zhang and D. L. Goeckel, “Multiple Access of Slightly Frequency-Shifted reference UWB Radio,” submitted to Globecom 2006.

[S12] A. O. Boryssenko, D. H. Schaubert, “On Optimal Port Loading Conditions for Maximizing Product of Energy and Gain Bandwidth in Broadband Antenna Links”, Submitted to IEEE Trans. Antenna & Propagation

Number of Manuscripts: 12.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED	
Sachit Chandra	0.50	No
Sanghyun Chang	0.25	No
Yi-Ling Chao	0.25	No
Yenming Chen	0.25	No
Meng-Hsuan Chung	0.25	No
Ziba Ebrahimian	0.25	No
Shaomin Hsu	0.50	No
Chun-Hsuan Kuo	0.25	No
Sangyoub Lee	0.25	No
Jongrit Lerdworatawee	0.50	No
Ali Medi	0.50	No
Majid Nemati-Anaraki	0.25	No
Durai Thirupathi	0.50	No
Yunkai Wang	0.25	No
Robert Wilson	0.50	No
On Wa Yeung	0.25	No
Liang Zhao	0.50	No
Mingrui Zhu	0.50	No
Sotorios Zogopoulos	0.50	No
Jonathan Tsao	0.50	No
Mike Chen	0.59	No
Stanley Wang	0.20	No
Ian O'Donnell	0.19	No
Michael Montero	0.06	No
Chen Chang	0.63	No
K. Litovsky	0.50	No
Sreenivas Kasturi	0.50	No
Christopher Yafrate	1.00	No
Alan Stigliani	0.50	No
Eric Marklein	1.00	No
Siqi Li	1.00	No
Sanquan Song	0.08	No
Qu Zhang	0.50	No
Yonggang Hao	0.50	No
Honglei Zhang	0.50	No
M. S. Nandakumar Anand	0.25	No
FTE Equivalent:	**15.50**	
Total Number:	**36**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED	
Anatoliy Boryssenko	0.32	No
Dana Porrat	1.00	No
FTE Equivalent:	**1.32**	
Total Number:	**2**	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Dan Schaubert	0.15	No
Dennis Goeckel	0.14	No
David Pozar	0.30	No
Won Namgoong	0.20	No
Keith Chugg	0.15	No
Robert Scholtz	0.20	No
Robert Brodersen	0.20	Yes
FTE Equivalent:	**1.34**	
Total Number:	**7**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Personnel receiving masters degrees

NAME	
M. S. Nandakumar Anand	No
Alan Stigliani	No
Christopher Yafrate	No
Sanquan Song	No
Siqi Li	No
Jonathan Tsao	No
Sanchit Chandra	No
Shaomin Shu	No
Total Number:	**8**

Names of personnel receiving PHDs

NAME	
Yi-Ling Chao	No
Jongrit Lerdworatawee	No
Durai Thirupathi	No
Yunkai Wang	No
Mingrui Zhu	No
Michael Montero	No
Ziba Ebrahimian	No
Chun-Hsuan Kuo	No
Sangyoub Lee	No
Ali Medi	No
Robert Wilson	No
Mike Chen	No
Stanley Wang	No
Ian O'Donnell	No
Chen Chang	No
Qu Zhang	No
Liang Zhao	No
Sotorios Zogopoulos	No
Total Number:	**18**

Names of other research staff

NAME	PERCENT_SUPPORTED	
F. Caron	0.07	No
K. Shimeld	0.27	No
P. Dufilie	1.00	No
Gerrielyn Ramos	0.25	No
Robert Weaver	0.60	No
Tom Boot	0.30	No
FTE Equivalent:	**2.49**	
Total Number:	**6**	

Sub Contractors (DD882)

1 a. University of California - Berkeley

1 b. Sponsored Projects Office
2150 Shattuck Avenue, Room 313
Berkeley CA 947045940

Sub Contractor Numbers (c): PO 65851
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e): Basic research on ultra-wideband radio
Sub Contract Award Date (f-1): 5/1/2001 12:00:00AM
Sub Contract Est Completion Date(f-2): 10/31/2006 12:00:00AM

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1 a. University of California - Berkeley

1 b. Sponsored Projects Office
336 Sproul Hall #5940
Berkeley CA 947205940

Sub Contractor Numbers (c): PO 65851
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e): Basic research on ultra-wideband radio
Sub Contract Award Date (f-1): 5/1/2001 12:00:00AM
Sub Contract Est Completion Date(f-2): 10/31/2006 12:00:00AM

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1 a. University of Massachusetts - Amherst

1 b. Office of Grant & Contract Administrati
408 Goodell Building
Amherst MA 010039272

Sub Contractor Numbers (c): PO 65852
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e): Basic research on ultra-wideband radio
Sub Contract Award Date (f-1): 5/1/2001 12:00:00AM
Sub Contract Est Completion Date(f-2): 10/31/2006 12:00:00AM

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1 a. University of Massachusetts - Amherst

1 b. Office of Grant & Contract Admin.
408 Goodell Building
Amherst MA 010033285

Sub Contractor Numbers (c): PO 65852
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e): Basic research on ultra-wideband radio
Sub Contract Award Date (f-1): 5/1/2001 12:00:00AM
Sub Contract Est Completion Date(f-2): 10/31/2006 12:00:00AM

Inventions (DD882)

5 **A Method for Secret Key Agreement in Cryptography**

Patent Filed in US? (5d-1) N

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Robert Wilson, Robert A. Scholtz, David Tse

5f-1a: U. of Southern California and U. of California at Berkeley

5f-c: University Park

Los Angeles CA 90089

5 **A Method for Transmitter Location in Multipath Environment**

Patent Filed in US? (5d-1) N

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Ziba Ebrahimian

5f-1a: U. of Southern California

5f-c: University Park

Los Angeles CA 90089

5 **Contoured triangular dipole antenna**

Patent Filed in US? (5d-1) N

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Alan Stigliani and Daniel Schaubert

5f-1a: University of Massachusetts

5f-c:

Amherst MA 01003

5 **Iterative Algorithm and Architecture for Fast Pseudo-Noise Acquisition Using Redundant Graphical Models**

Patent Filed in US? (5d-1) N

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Keith Chugg and On Wa Yeung

5f-1a: U. of Southern California

5f-c: University Park

Los Angeles CA 90089

5 **Ultra Wideband Loop Antenna**

Patent Filed in US? (5d-1) N

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Eric Marklein and Daniel Schaubert

5f-1a: University of Massachusetts

5f-c:

Amherst MA 01003

Final Technical Report
Short-Range Ultra-Wideband Systems
Contract No. DAAD19-01-1-0477
R. A. Scholtz, Principal Investigator

The Problems

The problems that we have singled out in this research have two characteristics: They are caused by the extreme fractional bandwidth of ultra-wideband (UWB) radio, and they cannot be solved directly by conventional means. Major topics include modeling UWB channels (especially for short range mobile and dense multipath links), antenna design for UWB links, coexistence with interference, energy capture for highly time-spread UWB signals, rapid sync acquisition techniques, low-power implementation issues, and compliance with FCC regulations.

The Organization

Because UWB systems must operate at the cutting edge in so many areas of technology, the principal investigator Bob Scholtz believed that UWB research must be driven by efforts to gain experience with real problems and real environments, and must be conducted by a research team that has capability across the broad spectrum of problems to be encountered in UWB radio research. Accordingly, he assembled the research team composed of antenna/rf experts David Pozar and Dan Schaubert at the University of Massachusetts (UMass), system architecture/chip implementation experts Bob Brodersen at the University of California (UC Berkeley) and Won Namgoong at the University of Southern California (USC), and system design experts David Tse at UC Berkeley, Dennis Goeckel at UMass, and Keith Chugg at USC.

Although not all the members of the team knew each other when the team was formed, as the research effort progressed, the group became a relatively close-knit team, with many inter-lab visits by faculty and students providing useful interactions. The UltRa Lab at USC provided UWB propagation measurement capability that was used by graduate students from all three schools. In addition, annual research reviews were preceded by one-day meetings at which faculty and participating graduate students could informally exchange ideas and results.

Major Contributions

This MURI research program has produced XX journal papers, YY conference papers, and ZZ manuscripts yet to be published, which contain detailed descriptions of many research results. The brief review presented here is the principal investigator's view of the major contributions made by the research team members, along with some key references.

When the UltRa Lab was formed, the two questions that most visitors asked were, "Do you have a link budget of a UWB radio?" and "What antenna are you using?" As r.f. bandwidth increases, these become very interesting questions because UWB antenna systems must be modeled as significant filtering operations.

- Pozar provided partial answers to these questions in [1]. There he illustrated the computation of energy link loss between two electrically short dipole antennas driven by Gaussian or Gaussian doublet waveforms, and showed that Friis equation used in narrowband link computations is not adequate for UWB free-space link-loss computations.
- Schaubert and Boryssenko developed a simulation tool (the UMass UWB Link Simulator) that integrates Spice time-domain circuit analysis with an improved version of their Time-Domain Integral-Equation (TDIE) full-wave electromagnetic simulator [2]. This tool allows a careful simulation of the behavior of electronic circuits attached to antennas [3], and made possible the determination of waveform distortion, energy transfer, etc., in UWB radio systems [4]. The UMass UWB Link Simulator was demonstrated at the MURI-sponsored UWB workshop in April 2006.
- Pozar used variational methods to optimize various properties (energy, peak value, sharpness) of received UWB signals under constraints on the input signal energy or available energy at the transmitter [5]. Solutions for the transmitted signals achieving these goals were determined analytically for electrically small dipoles and numerical results were obtained for large dipole antennas. (This work received the **S. A. Schelkunoff Award** from the *IEEE Antennas and Propagation Society*).
- The optimizing waveforms that Pozar determined in [5] above appeared difficult to achieve in practice. This led Boryssenko and Schaubert to use the UMass UWB Link Simulator to determine simple source waveforms (triangular or digitally generated) that produce desirable properties in the receiver [6]. Motivated by the FCC ruling in 2002, Lewis and Scholtz defined an FCC mask-filling efficiency and gave a few preliminary results of an ongoing search for digital signals that maximize this efficiency [7].

Our basic research program was originally constructed to support eventual applications to short-range, low-power , and relatively low data rate applications such as identify-friend-or-foe (IFF) systems, covert communications, RF tagging for autonomous manifesting, status monitoring systems, battlefield asset tracking, position monitoring, medical tagging, etc. Hardware implementation questions revolved around what could be implemented inexpensively with CMOS technology and support the required large bandwidths, and how much battery power would be required by such a UWB radio system. Brodersen and Namgoong led research efforts to answer these questions.

- Wang, Niknejad, and Brodersen [8] developed methods for representing small omni-directional antennas that made equalization/compensation in the transceiver for antenna dispersion possible. This work acknowledged some interaction with Pozar and Schaubert, and with Fleming and Kushner of Aether Wire and Location.
- Chen and Brodersen [9] developed a sub-sampling receiver front-end for operation in the 3.1 GHz to 10.6 GHz band prescribed by the FCC for UWB radio communications. The receiver used in-phase and quadrature (analytic) signal processing to mitigate timing error problems. The design was evaluated in the presence of a sinusoidal interference signal.

- O'Donnell and Brodersen [10] presents an impulse UWB transceiver design for the 0-960 MHz band for sensor network applications (< 1mW power consumption, ~100 kbps communication rate, 10 m range). The digital receiver processing is based on a time-interleaved bank of low-resolution A/D converters. This paper received the **Jack Neubauer Memorial Best System Paper Award** from the *IEEE Vehicular Technology Society*.
- Lerdworatawee and Namgoong [11] developed a new theoretical design procedure for low-noise amplifiers that is suitable for UWB applications. This procedure specifies the matching network in the LNA that maximizes the signal-to-noise ratio for matched filter detection.
- To protect against the narrowband interference that inevitably will confront UWB radio systems, Namgoong [12] developed a UWB receiver architecture that is channelized in the frequency domain to provide significant immunity against a large narrowband interferer.

The very fine time resolution characteristics of UWB radio systems means that the pulse response functions which characterize many real UWB channels have a structure that is unpredictable because of the unknown parameters of its resolvable multipath components. Transmitted-reference techniques provide a simple modulator and receiver architecture that uses all of the energy in the received signal, rather than the signal received over just one propagation path, to determine the transmitted information. The objective of this type modulation is ultra-low-complexity radio design (such a receiver pays a significant performance penalty at low signal-to-noise ratios).

- Following an approach suggested by Hoctor and Tomlinson of GE Research, MURI researchers explored transmitted-reference systems, a technique used in the 1950's to learn carrier structure in a spread-spectrum systems without a stored reference copy in the receiver. Chao and Scholtz at USC [13] analyzed the performance of various forms to transmitted reference radio receivers.
- Goeckel and Zhang developed an exceptionally simple and novel form of transmitted reference system, fulfilling the rationale for building transmitted-reference systems – namely low-complexity receivers [14], [15]. Four University of Massachusetts undergraduates constructed a fully functional ultra-wideband frequency-shifted reference (FSR-UWB) link as part of their senior design project, and demonstrated their system at the MURI-sponsored UWB workshop in April 2006.
- Feng and Namgoong extended the channelized UWB receiver architecture to support transmitted-reference signal processing [16]. Coarse acquisition in this channelized receivr architecture was shown to be significantly faster than in full-band UWB systems.

For a given timing uncertainty, the average time to acquire synchronization is typically expected to be inversely proportional to the bandwidth of the signal being sought, and hence the sync acquisition time for UWB signals was expected to be excessively large. MURI research has shown that this is not necessarily the case.

- Homier and Scholtz showed that when the time resolution is less than the multipath spread, acquisition is inversely proportional to the multipath spread rather than the

time resolution. Furthermore they exhibited an sync acquisition algorithm, called a bit reversal search, that is nearly optimal for most channels and requires on a priori information about the channel structure [17], [18]. This work received the **2003 IWUWBS Best Paper Award**.

- Zhu and Chugg adapted iterative message-passing algorithms to develop rapid acquisition algorithms that approximate maximum-likelihood synchronization processing [19], [20]. This approach is faster and more reliably at low signal-to-noise ratios than standard acquisition algorithms. This work, which applies generally to direct-sequence spread spectrum signals (UWB or not), received the **2003 Fred Ellersick Award** for the best unclassified paper at *MilCom 2003*. Yeung and Chugg [21] developed a hardware architecture to implement these rapid PN code acquisition algorithms.

A study of the structure of multipath that is resolved into distinguishable components by UWB transmissions recently has yielded interesting results. Indeed it is remarkable that the following research results all arise from researchers with differing backgrounds investigating UWB signals propagating through complex environments.

- Tse and Porrat [22] showed that under suitable conditions as bandwidth is increased in a multipath channel, power-constrained spread-spectrum signals can achieve the capacity of an additive white Gaussian noise channel by using an appropriate transmission duty cycle. The conditions under which this result holds is that the number of resolvable signal paths is sub-linear as a function of increasing signal bandwidth.
- Using the theory of reciprocity for electromagnetic propagation between antennas, Wilson, Tse, and Scholtz [23] proposed a secret key distribution method derived from the common information in the channel pulse response function. The viability of deriving a common random bit stream from pulse responses at each end of the link by publicly exchanging a small amount of information was demonstrated, and the level of protection against eavesdropping was explored.
- Boryssenko, et al. [24] developed a low-cost low-complexity UWB radar sensor for focusing and imaging through materials using a small receiving array. This system was demonstrated at the MURI-sponsored UWB radio workshop in 2006.

The complete collection of publications under this grant includes preliminary conference publications of theabove results, variations and extensions, and applications that have not been fully developed at the time that this MURI research contract reached its completion date.

Other Tangible Results

***Hardware fabricated*:**

- An LNA (<1Ghz) was fabricated in 0.13um CMOS technology and tested. The results were published in 2005 IEEE RFIC Symposium.
- UWB receiver and transmitter prototypes (operating above the GPS bands) were fabricated in 0.25um CMOS technology.

- "BEE" Berkeley Emulation Engine. This is an array of 20 FPGA's which allows the implementation of algorithms at up to 600 billion operations per second. A 1 Gigasample/second A/D board was built for interfacing analog UWB signals to this array. It was networked and available to interested parties.
- "CMOS chip design – Pulser" An H-bridge based pulser test chip was fabricated in .18 micron CMOS technology.
- A low-power sub-sampling ADC was fabricated in 0.13um CMOS technology and tested.
- The baseband (0-1GHz) impulse transceiver IC was fabricated in a 6-metal, 1-poly 0.13micron CMOS process. The chip contained all of the analog-front-end transmit and receive functionality with the back-end digital computation moved off-chip to provide flexibility for design space exploration.
- A 3-10GHz CMOS LNA is under fabrication in 0.13um CMOS technology and tested in September 2005.
- FPGA-based hardware implementation of rapid pseudo-noise code acquisition algorithm. This design is contained in a single Xilinx Virtex 2 device (XC2v250-6), using 28160 bits of block RAM, 1621 4-input look-up tables, and 1039 slices. The design runs at approximately 5 million pulses per second.
- Several UWB antennas operating 3-10 GHz. Provisional patent applications were filed for two of these designs.
- Several UWB antennas operating at low frequencies. These antennas were evaluated in a joint UMass/USC experiment at the USC antenna test range.
- Active patch antennas that can be tuned over wide bandwidth. These antennas are reasonably robust in the presence of metallic bodies and might be an alternative to instantaneous bandwidth antennas.
- Prototype models of a two-flare-shaped UWB antenna that has a unidirectional beam with moderate gain and very good characteristics for UWB communications and sensing.
- A UWB radar for short-range imaging in free space and a through-the-wall mode was fabricated and tested. Its signal processing exploited a small interferometer base with one transmit and two receive channels. This radar with its MTI-like processing was demonstrated at the MURI-sponsored UWB workshop in April 2006.
- Four University of Massachusetts undergraduates constructed a fully functional ultra-wideband frequency-shifted reference (FSR-UWB) link as part of their senior design project. This also was demonstrated at the MURI-sponsored UWB workshop in April 2006.
- A single-chip UWB transceiver was designed in 0.18 micron CMOS technology to operate in the 3.25-4.75 GHz band and to achieve data rates in excess of 1 GHz.

***Operational Software*:**

- "UMass UWB Link Simulator" Antenna and EM link simulator (partially funded by ASTRON and DSO National Labs).

***Data Bases available*:**

- UWB Propagation Data Base on the UltRa Lab web site, accessible over the Internet at http://ultra.usc.edu/New_Site/database.html (funded in part by Intel and Microsoft). This data base has been used by many other investigators to support their research.

Sponsored Meetings

In addition to the ZZ talks given at various technical meetings and listed in the final report, this MURI project initiated several meetings, open to external researchers, at which MURI team members and others gave presentations on their UWB radio research/interests.

- First Annual Research Review (May 23, 2002, in Baltimore MD near the end of the IEEE's UWB Conference): This meeting, which drew approximately 35 attendees, featured presentations by the MURI investigators, Steve Griggs (NETEX program, DARPA) and Steve Gunderson (Total Asset Visibility Program, NFESC).
- Co-sponsored Workshop: The Intel Corporation and the UWB MURI team sponsored a UWB Workshop on October 3-4, 2002, at the University of Southern California, just prior to MILCOM '02 in San Diego. Attempts were made to close registration at 120 attendees, but the attendance swelled to more than 150 attendees. In addition to panels with liberal time for questions, the workshop featured Edmond Thomas, Chief of the FCC's Engineering and Technology Office as banquet speaker, who stated the FCC's view of UWB regulation. Viewgraphs from most of the presenters can be found at http://commsci1.usc.edu/INTEL-USC/agenda.html. Thirty attendees toured the UltRa Lab's facilities after the workshop.
- Second Annual Research Review (August 20, 2003, Alexandria, VA): Government attendees: William Sander, Bob Ullman, Brian Sadler, (ARO,ARL); Leonard Miller, Nader Moayeri (NIST); Eric Mokole (NRL) Other attendees in addition to the MURI team: Nathaniel August, Woo Cheol Chung, Sajay Jose, Hun Kye Lee, Shen Wang (Virginia Tech); Patrick Houghton (Aether Wire and Location).
- NIST Meeting: In 2003 Scholtz and several students visited NIST to talk about their UWB efforts with NIST engineers in Bob Johnk's electromagnetics metrology lab, and to deliver possible UWB reference antennas for calibration. A second visit to NIST occurred when the Ando signal generator which was tested in the UltRa Lab was transferred to NIST. A grad student was sent to observe NIST's UWB measurement techniques.
- Third Annual Research Review (November 4, 2004, Monterey CA): This event drew 21 participants (faculty and graduate students) from the MURI team and approximately 20 attendees from the government and industrial community. This was scheduled the day after the Milcom Conference in Monterey, to make it easy to attend both events. CDs containing all presentations at the review and publications to date were made available to attendees and interested parties.
- Workshop on Short-Range Ultra-wideband Radio Systems (April 12-13, 2006, Santa Monica CA): Co-sponsored by the Army Research Office and the USC Communication Sciences Institute, this event was attended by 91 people from 6 different countries, representing 8 government labs, 17 companies and 15 universities. The workshop consisted of four panel discussions: (1) UWB Radio – Military Interests, (2) UWB Hardware, (3) UWB Systems, and (4) UWB Opportunities and Issues; a special address by Ron Chase of the FCC, 40 poster presentations, and 5 demonstrations. The workshop proceedings were recorded on a CD and copies were sent to all attendees. Discussions were video recorded. All MURI faculty and virtually all current MURI graduate students participated on panels or gave poster presentations.

Awards

- Bob Scholtz received the **2001 Military Communications Conference Award for Technical Achievement**. Among his publications that this life-time award honors is his first paper (1993) on a communication-theoretic analysis of a UWB radio system.
- Won Namgoong received a **2001 NSF PECASE Award** to work on high-performance UWB radio. The proposal focuses on developing general transceiver design techniques for high-bandwidth communication systems with emphasis on high-data-rate UWB radio.
- Jean Marc Cramer, Bob Scholtz, and Moe Win received the **2003 S. A. Schelkunoff Award** from the *IEEE Antennas and Propagation Society* for the paper "An evaluation of the Ultra-Wideband Propagation Channel." This paper was based on pre-MURI work.)
- Eric Homier and Bob Scholtz received the **2003 IWUWBS Best Paper Award** for the coauthored paper, "Hybrid Fixed-Dwell-Time Search Techniques for Rapid Acquisition of UWB Signals", presented by the *International Workshop on Ultra-Wideband Systems.*
- Mingrui Zhu and Keith Chugg received the **2003 Fred Ellersick Award** for the best unclassified paper at *MilCom 2003* for their MURI-supported paper "Iterative Message-Passing Algorithms for Rapid PN Code Acquistion."
- David Pozar received the **2004 S. A. Schelkunoff Award** from the *IEEE Antennas and Propagation Society* for the MURI-sponsored paper "Waveform Optimizations for Ultra Wideband Radio Systems."
- In 2004, Stanley Wang at UC Berkeley received an **Intel Fellowship** for his work on UWB implementation.
- Ian O'Donnell received the **Jack Neubauer Memorial Best System Paper Award** from the *IEEE Vehicular Society* for his September 2005 MURI-sponsored paper on UWB transceiver architectures. The award was presented at the 64th IEEE Vehicular Technology Conference in Montreal in September 2006.
- Bob Scholtz and Moe Win received the **2006 Eric E. Sumner Award** (an IEEE Field Award) "for pioneering contributions to ultra-wide band communications science and technology."This award was presented at Globecom 2006 in San Francisco in November 2006.

References

[1] David M. Pozar, "Closed-Form Approximations for Link Loss in an UWB Radio System Using Small Antennas," *IEEE Trans. Antennas and Propagation*, September 2003.

[2] Anatoliy O. Boryssenko and Daniel H. Schaubert, "Time-Domain Integral-Equation-Based Solver for Transient and Broadband Problems in Electromagnetics," *The AMEREM 2002 Symposium*, Annapolis, MD, June 2-7, 2002.

[3] A.O. Boryssenko, D.H. Schaubert, "Optimized Antenna and Signal Co-Design for UWB Antenna Link," *Ultra-Wideband Short-Pulse Electromagnetics 7*, 2006.

[4] A. O. Boryssenko and D. H.Schaubert, “Electromagnetics-Related Aspects of Signaling and Signal Processing for UWB Short Range Radios,” *J. VLSI Signal Processing (special issue on Ultrawideband Systems),* April 2006, v. 43(1) pp. 89-104.
[5] David M. Pozar, “Waveform Optimizations for Ultra-Wideband Radio Systems,” *IEEE Transactions on Antennas and Propagation*, September 2003.
[6] A.O. Boryssenko and D.H. Schaubert, “Efficient and Practical Pulses for Dipole Antenna UWB Link”, *Proceeding of IEEE Antenna & Propagation Symposium*, vol. 2, June 2004, pp. 1283-1286.
[7] T. Lewis and R. Scholtz, “Optimal UWB Waveform Synthesis with Power Spectral Density Constraints,” *Asilomar Conference on Signals, Systems, and Computers*, November 2004.
[8] S. Wang, A. Niknejad and R. Brodersen, “Circuit Modeling Methodology for UWB Omnidirectional Small Antennas,” *IEEE Journal of Selected Areas in Communications: Special Issue on Ultra-wideband Communications (Special Issue on Ultra-Wideband Wireless Communications – Theory and Applications),* v.24(4), April 2006, pp. 871-877.
[9] Mike S.W. Chen, R. Brodersen, “A Subsampling UWB Impulse Radio Architecture Utilizing Analytic Signaling,” *IEICE Trans. on Electronics*, vol. E88-C, No. 6, June 2005 (invited paper).
[10] I. D. O'Donnell, R. W. Brodersen, “An Ultra-Wideband Transceiver Architecture for Low Power, Low Rate, Wireless Systems,” *IEEE Trans. on Vehicular Technology (Special Section on Ultra-wideband (UWB) Wireless Communications – A New Horizon)*, v. 54(5), September 2005, pp. pp. 1623-1631.
[11] J. Lerdworatawee, W. Namgoong, “Low Noise Amplifier Design for Ultra-Wideband Radio”, *IEEE Trans. on Circuits and Systems I - Regular Papers*, vol. 51, June 2004, pp. 1075-1087.
[12] W. Namgoong, “A Channelized Digital Ultra-Wideband Receiver,” *IEEE Transactions on Wireless Communications*, May 2003, pp. 502-510.
[13] Y. Chao and R. Scholtz, “Ultra-Wideband Transmitted Reference Systems,” *IEEE Trans. on Vehicular Technology* (Special Section on Ultra-wideband (UWB) Wireless Communications – A New Horizon), v. 54(5), September 2005, pp. 1556-1569.
[14] D. Goeckel and Q. Zhang, “Slightly Frequency-Shifted Reference Ultra-Wideband (UWB) Radio: TR-UWB without the Delay Element,” *2005 Military Communications Conference*, October 2005.
[15] D. Goeckel and Q. Zhang, "Slightly Frequency-Shifted Ultra-Wideband (UWB) Radio," submitted to *IEEE Transactions on Communications.*
[16] L. Feng and W. Namgoong, “An Analog/Digital Baseband Processor Design of a UWB Channelized Receiver for Transmitted Reference Signals,” *J. VLSI Signal Processing (special issue on Ultrawideband Systems),* April 2006, v. 43(1) pp. 59-71.
[17] E. Homier and R. Scholtz, “Hybrid Fixed-Dwell Time Search Techniques for Rapid Acquisition of Ultra-Wideband Signals,” *International Workshop on Ultra-Wideband Systems*, Oulu, Finland, June 2003.
[18] Eric Homier and R. A. Scholtz, “A Generalized Signal Flow Graph Approach for Hybrid Acquisition of Ultra-Wideband Signals”, *International Journal of Wireless Information Networks (Special Issue on Ultrawideband Radio),* October 2003.

[19] M. Zhu and K. M. Chugg, "Iterative Message-Passing Algorithms for Rapid PN Code Acquisition," *IEEE Conference on Military Communications (MILCOM*), Boston, MA, November 2003.
[20] Keith M. Chugg and Mingrui Zhu, "A New Approach to rapid PN Code Acquisition Using Iterative Message Passing Techniques," *IEEE Journal of Selected Areas in Communications (Special Issue on Military Communications)*, vol. 23, no. 5, May 2005, pp. 884-897.
[21] O. W. Yeung and K. M. Chugg, "An Iterative Algorithm and Low Complexity Hardware Architecture for Fast Acquisition of PN Codes in UWB Systems", *J. VLSI Signal Processing (special issue on Ultrawideband Systems),* April 2006.
[22] D. Porrat, D. N. C. Tse and S. Nacu, "Channel Uncertainty in Ultra Wideband Communication Systems," *IEEE Transactions on Information Theory*, accepted pending revisions.
[23] R. Wilson, R. A. Scholtz, and D. Tse, "Channel Identification: Secret Sharing Using Reciprocity in Ultrawideband Channels," accepted by *IEEE Transactions on Information Forensics and Security.*
[24] D.L. Sostanovsky, A.O. Boryssenko, E.S. Boryssenko, "UWB Radar Imaging System with Two-Element Receiving Array Antenna," *5th International Conference on Antenna Theory and Technique*, Kiev, Ukraine, May 2005, pp. 357-360.